AUTOCYCLIC AND ALLOCYCLIC CONTROLS ON THE ORIGIN OF THE DUNKARD GROUP

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INTRODUCTION

Beerbower (1964) developed the concepts of autocyclic and allocyclic controls on sedimentation and stratigraphy on the basis of his work on the origin of the Dunkard Group and the voluminous previous work on the origin of Pennsylvanian cyclothems (Beerbower, 1961). According to Beerbower (1964) autocyclic processes include the redistribution of energy and materials within a sedimentary system such as stream meandering, channel avulsion, delta switching, etc. In contrast, allocyclic processes include changes in energy and materials within a sedimentary system induced by processes external to the sedimentary system. Allocyclic processes include eustatic, tectonic, and climatic change. Beerbower (1969, p. 1843) summarized his concepts as follows:

> In a general sedimentary model, cyclic deposits may be regarded as autocyclic or allocyclic (Beerbower, 1964, p. 32). The former are generated changes in sedimentary environment inherent in the sedimentation process, for example, delta switching. The latter are independent of particular depositional events, are generated outside the depositional unit and include tectonic, eustatic, and climatic cycles. Therefore, full interpretation of an alluvial cyclic deposit requires separation of autocyclic and allocyclic phenomena and isolation of the several particular causes of cyclicity.

The concepts of autocyclic and allocyclic processes are perhaps the most powerful diagnostic methods available to stratigraphers and sedimentologists for the analysis of the origin of sedimentary rocks because these concepts provide a comprehensive, integrated, diagnostic, analytical framework (e.g., Busch and Rollins, 1984). Sequence stratigraphy, which has come into vogue amongst stratigraphers during the past two decades, evaluates the eustatic variable of allocyclic analysis while overlooking climatic and tectonic change as well as autocyclic processes. An example of the short comings of a single variable sequence stratigraphic model can be illustrated by the sequence stratigraphy of coal-bearing sequences that were deposited under a humid climate while contemporaneous eustatic changes in an arid climate result in eolianites and carbonates, a totally different lithostratigraphic response to the same eustatic event (Cecil et al., 2003a).

Although autocyclic processes may result in cyclic deposition in that they repeat, they are without a predetermined frequency. Consequently, they are aperiodic because they do not represent a determinate period of time. The same can be said for allocyclic tectonic change. The sedimentary response to autocyclic processes tend to be rather local and they generally do not produce regionally mappable units. In contrast, allocyclic changes in precipitation and sea level may be the result of deterministic processes that are periodic, such as orbital forcing. Thus,

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periodic changes in sea level and (or) precipitation led to predictable sedimentary cycles such as the well known Pennsylvanian cyclothems (e.g., Busch and Rollins, 1984).

Deposition of the Dunkard Group has been attributed to fluvial-deltaic processes including aggradation on an alluvial plain and lacustrine deposition (e.g., Beerbower, 1961, 1964, 1969; Berryhill and Swanson, 1962; Berryhill, 1963; Martin, 1998). Autocyclic processes that controlled the origin of the Dunkard Group have been explicitly evaluated and summarized by Beerbower (1969) and implicitly by Martin (1998). Beerbower (1969) attributed alluvial plain aggradation in the southern region of the Dunkard Group to autocyclic processes. Because autocyclic process controlled aggradation in the alluvial plain, marker beds are rare and geologic mapping of alluvial plain time-stratigraphic units is exceedingly difficult. However, allocyclic processes were the predominant control on the stratigraphy of the Dunkard Group in the lacustrine basin where marker beds such as coal bed horizons, limestone horizons, and regional-scale paleosols are rather widespread and mappable. Allocyclic processes are further evaluated herein.

Relative Importance of Autocyclic Processes

As pointed out by Beerbower (1969), autocyclicity was the predominant control on alluvial plain deposition. Alluvial plain deposition is most extensively developed in the southern and southeastern part of the basin in central West Virginia. The alluvial plain environment is interpreted herein as a low gradient alluvial fan where the gradient is estimated to have been approximately 5.28 m per km (1 ft per mi). Anastomosing streams likely crisscrossed the aggrading fan. Autocyclic channel avulsion was common, resulting in channel incision as new streams flowed down the regional gradient of the fan. Root traces commonly occur in channel fills, levees, and over-bank deposits in the basin center indicating low-flow conditions and prograding alluvial plain aggradation when lacustrine conditions were absent (Figure 1).

Relative Importance of Allocyclic Processes

Changes in precipitation were the predominant direct allocyclic control on Dunkard Group lithostratigraphy. Variations in precipitation controlled variations in terrestrial organic productivity, lacustrine base levels, basin-scale weathering, water table and pedogenesis, sediment supply, soil moisture, and sedimentary geochemistry. Tectonics controlled accommodation space and basin configuration. Tectonic controls on basin configuration may have included occasional tectonic development of a silled basin, which contributed to lacustrine accommodation space. Although the presence of sills has not been documented, they can be inferred. As will be discussed subsequently, tectonically induced rain shadow effects may have contributed to the period-scale climatic drying trend that began during deposition of the Late Pennsylvanian Monongahela Group (Cecil et al.,1985; Cecil. 1990). In contrast to climate and tectonics, eustasy had little or no recognizable effect on the stratigraphy of the Dunkard Group as fully marine conditions have never been documented within the ~366 m (~1,200 ft) of Dunkard strata. One incursion of brackish water may be indicated by an occurrence of *Lingua* in a dark shale parting within the Washington coal complex (see Stop 2 description). The known spatial distribution of the *Lingula*-bearing bed is confined to a relatively small geographic area in the vicinity of the Ohio River and its tributaries in Marshall County, West

Figure 1. Root penetrations nearly destroyed the original bedding in channel fill sandstone, levee, and over-bank deposits near the basin center. Important sedimentological features indicated here include the replacement of lacustrine conditions by alluvial plain progradation and aggradation, and rizomorphs indicative of aquatic vegetation demonstrating low-flow conditions in all depositional environments. Photo is approximately 52 m (170 ft) above the Waynesburg coal bed in the Brick Hill section near Moundsville, WV.

Virginia and Belmont County, Ohio (Cross et al., 1950). Of the three-allocyclic processes, climate was the predominant control on lithostratigraphy and will be discussed in more detail.

Climate and Climate States

Climate refers to average long-term weather (Bates and Jackson, 1987, p. 125). A climate state, as used herein, refers to a climate that prevailed in a region for an extended period. Thus, major shifts in climate are referred to as a change in state. Use of climate state terminology is preferable to such terms as greenhouse or ice house because climate state terminology does not implicitly or explicitly imply cause. The duration of paleoclimate states are defined in Table 1.

Carboniferous and Permian paleoclimate states in the Appalachian basin appear to have persisted at multiple time scales (Bush and Rollins, 1984; Cecil et. al., 1985, Cecil, 1990), ranging from tens of millions of years to a few thousand years (Table 1). Climate variations shorter than one thousand years are assigned herein to variations in weather. The hierarchy of time scales in Table 1 provides a convenient method of expressing the duration of prevailing climate states without implying causes or controls.

The three predominant components of climate are temperature, wind, and precipitation. Most workers use mean-annual precipitation to estimate and describe paleo-precipitation (e.g., Retallack, 1990). However, seasonality of rainfall (Table 2) is a more

Table 1. Duration of paleoclimate states using terminology modified from glacial and interglacial time scales. (Adapted from the AGI Glossary of Geology).

Time scale	Duration
Period	10 My
Epoch	1 My
Stage	10^2 Ky
Age	10 Ky
Stage	1 Ky
Weather	< 1 Ky

quantitative measure of climate as a control on pedogenesis, sediment supply, sedimentation, and stratigraphy (Cecil and Dulong, 2003). The climate classification in Table 2 is based on the number of months in a year that rainfall exceeds evapotranspiration, a classification that implicitly indicates a degree of monsoonal atmospheric circulation. However, it is possible, and even probable, that an ambient climate may have a relatively weak annual rainy season when rainfall does not exceed evapotranspiration. In the latter case, the climate would be designated as arid using the classification in Table 2. Although an arid climate designation is technically correct, given the physical parameters specified in Table 2, plants, soils, and sediment yield would respond and record weak seasonality in precipitation. The predominant paleoclimate states that controlled deposition of Dunkard strata were determined by seasonality of precipitation, even if there was a weak annual rainy season.

Climate and Soil Moisture

Climate seasonality is one of the principal factors that controls pedogenesis and soil properties, including soil moisture (Table 2) (Cecil and Dulong, 2003). Since the appearance of land plants, soil moisture must have been a first-order control on plant ecology and the production of terrestrial organic matter. Terrestrial organic matter is important in soil genesis because the amount of organic matter is a predominant control on soil pH and Eh which, in turn, are key controls on pedogenesis. Thus, paleosol properties can be used to estimate soil moisture, even though it is not possible to measure soil moisture directly, as is possible in

Table 2. Annual precipitation regimes, the degree of seasonality, and probable soil moisture based on the number of consecutive wet months per year in regions that were warm, had a low elevation, and a low surface gradient. By definition, a month is wet when rainfall exceeds evapotranspiration (modified from Cecil, 2003, p. 3-4, and Cecil and Dulong, 2003).

Number of wet months	Precipitation regime	Degree of seasonality	Probable soil moisture
0	Arid	Aseasonal	Aridic
1-2	Semiarid	Minimal	Aridic to Ustic
3-5	Dry subhumid	Maximum	Ustic
6-8	Moist subhumid	Medial	Udic
9-11	Humid	Minimal	Aquic
12	Perhumid	Aseasonal	Peraquic

Table 3. Soil orders and their probable soil moisture regimes (see Cecil and Dulong, 2003 for more details).

Soil order	Soil moisture	Comment
Aridisols	Aridic	Mostly dry throughout the year
Molisols, Alfisols, Vertisols	Ustic	Dry throughout most of the year
Vertisols	Udic	Moist for a significant part of the year
Oxisols, Ultisols, and Spodosols	Aquic	Moist throughout most of the year
Histosols	Peraquic	Water logged most or all of the year

modern soils. A qualitative estimate of soil moisture regimes for various soil orders is presented in Table 3.

AUTOCYCLIC AND ALLOCYCLIC CONTROLS ON DEPOSITIONAL SYSTEMS

Late Paleozoic Paleoclimate

On the basis of changes in paleoclimate indicators in Paleozoic strata, examples of both abrupt and gradational shifts in period-scale paleoclimate states can be found in the Central Appalachian basin (Cecil et al., 2004, p. 85, fig. 10). For the Permo-Carboniferous, a 10 My humid period that began in the late Devonian continued through the early Mississippian but ended abruptly at approximately the end of the Tournaisian. A 15 My early Mississippian humid period was punctuated by stage-scale climate and sea-level cycles. Subsequently, period -scale sea-level rise was accompanied by a 19 My middle Mississippian arid period (Visean) across North America. The Visean aridity began to gradually end at approximately the beginning of the Serpukhovian when eustatic sea level fall exposed the top of the Greenbrier Limestone (Alderson Limestone Member, southeastern West Virginia), coeval with the onset of a dry-subhumid climate. The karsted Greenbrier surface is overlain by siliciclastics that were delivered to the basin by an increase in fluvial sediment supply in response to the shift from Visean aridity to the increase in seasonal rainfall in the early Serpukhovian.

In the central Appalachian basin, the climate of the subsequent 8 My late Mississippian (Serpukhovian) became increasingly moist, progressing from Visean aridity to dry-subhumid in the earliest Serpukhovian to moist-subhumid by the end of the Serpukhovian (Cecil, 1990; Cecil et al., 2004) as global sea level continued to fall. Increasingly humid conditions are indicated by the late Serpukhovian by the development of humid climate paleosols including thin but mappable coal beds in late Serpukhovian strata. The moist-subhumid climate ended abruptly at approximately the Mississippian-Pennsylvanian boundary when the dry-subhumid climate of the latest Mississippian (latest Serpukhovian) changed to an Early Pennsylvanian (Bashkirian) humid to perhumid climate (Cecil et al., 1985; Cecil, 1990; Cecil et al., 2004). The Early Pennsylvanian humid climate persisted for approximately 6 My. The humid climate was coeval with maximum high-latitude continental ice volume and a maximum low stand in sea level that produced the mid-Carboniferous eustatic event (Saunders and Ramsbottom, 1986), and an unconformity of global proportions. The 6 My humid period led to chemical weathering and erosion that produced erosional surfaces, residual deposits, and karsting not only in much of the Appalachian basin but across the North American craton. Mid-Carboniferous residual weathering deposits include, but are not limited to, the following: a) Mercer clay in Pennsylvania, b) Olive Hill clay in Kentucky, c) Cheltenham clay on the Ozark dome and adjacent plareau in Missouri, d) residual chert ("chat" term used by the Kansas Geological Survey) in southeastern Kansas, and e) the Molas Formation in Colorado. Paleo-karsting is well developed on Mississippian limestones in Kentucky, the Madison Limestone in Colorado, and the top of the Guernsey Limestone (Madison Limestone equivalent) in Wyoming and Montana. Erosional surfaces at the Mid-Carboniferous boundary are common in numerous basins across the craton. Although there may have been a modest east-to-west drying gradient, the humid climate of the Early and early Middle Pennsylvanian persisted across the craton until near the end of the Bashkirian (late Atokan) when continental ice began to melt, global sea level slowly rose, accompanied by gradual temporal drying as documented in the Appalachian basin (Cecil et al., 1985; Cecil, 1990). Spatial and temporal Atokan sea level rise and gradual continental flooding is indicated by the onset of widespread sedimentation across the cratonic unconformity well beyond the extent of Morrowan strata (McKee and Crosby, 1975). Morrowan strata appear to be confined to cratonic depressions of various origins.

Period-scale gradual drying continued, interrupted by stage-scale climate and sea level cycles, as sea level gradually rose and continental ice sheets melted until the Kasimovian (Missourian). Maximum drying is indicated in the Appalachian basin at about the Kasimovian-Gzhelian (Missourian-Virgilian) boundary. Maximum drying is also indicated at the same time in Arrow Canyon, Nevada, by evaporative gypsum rosettes in Missourian age limestones. This was also a time of maximum highstand in sea level and minimal ice volume (Rygel et al., 2008). The Ames marine zone, the last known fully marine incursion into the Appalachian basin (early to middle Kasimovian; Edmunds, 1996, Lebold and Kammer, 2006), may represent the maximum high stand during the Late Pennsylvanian. The absence of subsequent sea level transgressions make it nearly impossible to identify linkages among sea level, climate, and high -latitude ice volume for either period- or stage-scale climate systems for the remainder of the Pennsylvanian and Permian. However, available paleoclimate proxies indicate that precipitation gradually decreased throughout deposition of the Dunkard Group, possibly for more than 10 My. Unlike the Carboniferous, where abrupt lithostratigraphic changes document changes in period-scale climate states, there is no clear stratigraphic evidence indicative of a distinct climate period during deposition of the Dunkard Group. Nor is there obvious evidence in the Appalachian basin to suggest eustatic changes in sea level or ice volume, even though stage-scale sea-level changes occurred in the Early Permian of Kansas and elsewhere across the craton. Rather, it is clear that the climate-drying trend that began in the later Middle Pennsylvanian into the late Pennsylvanian (Cecil, 1990; Roscher and Schneider, 2006) continued, interrupted intermittently by stage-scale shifts in climate state, throughout deposition of the Dunkard Group. There is no discernable evidence indicating that there were significant climatically induced changes in temperature during Dunkard deposition. If so, the equitable temperatures in the Appalachian basin can be attributed to an equatorial paleogeography (see paleogeographic reconstructions by Scotese, 2001).

During the Pennsylvanian, maximum precipitation in the tropics was associated with stationary low pressure systems that developed during maximum ice volume and maximum lowstands, regardless of the duration of climate states (Cecil, 1990). Peat precursors to coal formed during stage-scale, low stand, humid conditions. As Pennsylvanian ice sheets melted, rising sea level flooded cratonic basins while the low-stand humid climate and atmospheric low pressure doldrums gave way to high pressure and cross-equatorial surface winds. The high pressure systems induced wind-driven circulation in the shallow epeiric seas, which shut down dysoxic conditions and the deposition of organic-rich mud (black shale) while turning on the carbonate factory (Cecil et al., 2003a). Climate drying and monsoonal circulation were maximized during interglacials and maximum high stand conditions, regardless of paleolatitude across the craton (Cecil, et al., 2003a ; Cecil, et al., 2004). During high stands, open marine limestones were deposited off shore while nonmarine limestones were deposited contemporaneously in continental lacustrine systems. However, linkages among ice volume, sea level, and paleoclimate during deposition of the Dunkard remain equivocal because of the absence of marine incursions into the Appalachian basin. Regardless, the importance of climate as a control on Permo-Carboniferous stratigraphy cannot be overstated.

Terrestrial Organic Productivity

Papers by DiMichele et al., Blake and Gillespie, and Eble et al. (2011) present a comprehensive overview of the state of knowledge of the paleobotany of the Dunkard Group. Thus, the observations present herein are limited to field evidence for apparent climate controls on stratigraphic variations in terrestrial organic productivity. Temporal variations in terrestrial organic productivity were probably controlled by both period- and stage-scale climatic variations in rainfall. In general, it appears that terrestrial organic productivity was diminished during deposition of Dunkard strata relative to the preceding Pennsylvanian because of period-scale climate drying. This is especially true for the Greene Formation where plant fossils are relatively uncommon and coal beds are relatively thin, discontinuous, and impure. Coal bed horizons above the Washington coal complex at the base of the Washington Formation are little more than spatially recognizable centimeter-scale coal bed horizons or coaly streaks generally overlying poorly developed underclay paleosols (see Fedorko and Skema, 2011, for the stratigraphy of coal beds in the Dunkard Group). Root traces occur commonly throughout aggraded alluvial plain deposits, including some channel sandstones, suggesting the following: a) aquatic plants were common, b) streams were shallow, and c) stream flow was low.

Sedimentary Geochemistry

The significance of the sedimentary geochemistry of the Dunkard Group is perhaps best illustrated by a comparison with the Morrowan Pocahontas and New River formations, and the Atokan Kanawha Formation (Bashkirian into the Moscovian). These formations contain the low-sulfur bituminous coal beds of southern West Virginia (for additional lithostratigraphic details see Cecil et. al., 1985, p. 17, tab. 4). Calcareous strata are extremely rare in Early and early Middle Pennsylvanian strata, being found only in the occasional concretion that formed in rocks deposited under marine influence, most often in the early Middle Pennsylvanian Kanawha Formation. In contrast, nonmarine limestones are common in the lower part of the Dunkard, and Dunkard strata become increasingly calcareous up-section, particularly in the Greene Formation. Nonmarine limestones grade into coeval petrocalcic paleo-Vertisols in the alluvial plain reflecting both a paleosol catena (paleotopography) and dry climatic conditions of calcium carbonate deposition, be it lacustrine or pedogenic carbonate.

Much of the iron in Early and early Middle Pennsylvanian strata is in the ferrous state, occuring in abundant siderite (Cecil et al., 1985). Conversely, a significant amount of iron occurs in oxidized forms in red beds in the Dunkard. The comparatively minor amounts of reduced iron in the Dunkard occurs in relatively small amounts in siderite, predominantly in the Waynesburg Formation and the lower half of the Washington Formation. Additional reduced iron occurs in pyrite, mostly associated with coal beds. In contrast, siderite is very abundant in Early and early Middle Pennsylvanian strata whereas pyrite occurs only in trace amounts. The major contrast in the mineralogical distribution of iron among the Early through early Middle Pennsylvanian strata and Dunkard Group strata is indicative of major differences in sedimentary geochemistry.

The original major coal resources in Early and early Middle Pennsylvanian strata also contrast with the extremely meager coal resources of the Dunkard Group (upper barren measures of Rogers, 1858). Furthermore, kaolinite is the predominant clay mineral, by far, in Early and Middle Pennsylvanian underclay paleosols, including the Allegheny Formation. These paleosols were subjected to subaerial exposure, weathering, and pedogenesis. The kaolinite-rich underclays are diagnostic indicators of intense chemical weathering during stage-scale low-stands and pedogenesis. The acidic and reducing pedogenic conditions were sufficient to cause the reduction and removal of iron, either by illuviation and precipitation in a B_S soil horizon (Spodic horizon), or by dissolution and outflow through fluvial systems on colloidial organic matter, or as dissolved ferrous iron. In contrast, Dunkard paleosols are commonly calcareous, and they generally do not exhibit characteristics of intense chemical leaching.

The major differences in the occurrence and concentration of syngenetic minerals in the southern coal fields of West Virginia and the Dunkard are indicative of relative extremes in syndepositional Eh and pH conditions. Surficial waters during deposition of nonmarine strata in the southern coal fields generally must have been acidic with a pH perhaps as low as 4.5 analogous to rivers draining the regions of ombrogenous peat deposits in the perhumid region of equatorial Indonesia (Cecil et al, 2003b). Such low pH values preclude the formation of calcite. During deposition of the Early and early Middle Pennsylvanian strata, the Eh was at least mildly reducing with values as low as -0.4V to -0.6V, all that is required to reduce iron under acidic conditions (see Garrels and Christ, 1965, p. 234). Given the ubiquitous calcite in Dunkard strata, the general pH condition during deposition of the Dunkard must have been alkaline, ≥ pH 8. The Eh probably was never less than 0.2V, except possibly during deposition of the sparse organic-rich deposits.

Uniquely different water chemistries are required to explain the differences in the lithologic characteristics among Early Pennsylvanian rocks in southern West Virginia and the much younger Dunkard Group. The different water chemistries were almost assuredly caused by differences in paleoclimate (Cecil et al., 1985; Cecil, 1990). The Early Pennsylvanian was dominated by a humid to perhumid climate whereas the Late Pennsylvanian and early Permian were controlled by climate extremes (Cecil, 1990) that may have ranged from semiarid during the formation of calcic paleosols to humid during peat formation. Acidic black water rivers, analogous to modern streams in equatorial Indonesia, with a pH as low as 4.5 (Cecil et al., 2003b), dominated fluvial systems and estuaries during the Early and early Middle Pennsylvanian. Concentrations of dissolved solutes in fluvial systems were very low, but the Eh-pH of continental hydrologic systems were sufficient to reduce and transport both dissolved and collodial iron to depositional environments where the iron was precipitated in the ferrous state as siderite. In addition, the humid climate resulted in intense chemical weathering that ultimately resulted in oligotrophic nutrient conditions that included all surface drainages, surficial waters and paleosols.

Figure 2. Alternating red and gray-green strata in the Dunkard alluvial plain. Guard rail (bottom) and light pole (left side of photo) provide scales. Road cut is on US 50 bypass near Parkersburg, WV.

In contrast to the acidic waters of the Early Pennsylvanian, low gradient muddy alkaline rivers, saturated by dissolved solutes such as calcium carbonate, criss-crossed the Dunkard landscape. Oxidizing conditions in the well-drained alluvial plain gave way to reducing conditions whenever and wherever waterlogging or flooding occurred during pluvial climate states, particularly in the lacustrine basin center. Alternating red and gray-green strata in the upper alluvial plain **(**Figure 2**)** are herein attributed to fluctuations in oxidizing and reducing conditions driven by stage-scale allocyclic changes in precipitation. Oxidizing conditions prevailed during dry periods when water tables were relatively low and vegetation on the alluvial plain landscape was sparse. Reduction of iron on the alluvial plain occurred during relatively humid periods when soil moisture was high, terrestrial organic matter was abundant, and the water table was at or above the surface in the lacustrine basin.

Intra- and Extra-Basinal Weathering

Climate-driven physical and chemical weathering are always a factor in pedogenesis and sediment production. The nature of intra-basinal weathering during Dunkard deposition is indicated by physical and chemical properties of paleosols, and the textural and mineralogical properties of fluvial sediments. If any sediment was derived from outside the basin, then weathering in extra-basinal provenance regions is also indicated by the textural and mineralogical properties of fluvial sediments. If there were differences in weathering in either of these environments, they are not apparent in field observations. Repeated occurrences of wacke sandstones as well as an increase in the occurrence of petrocalcic paleo-Vertisols indicate that there was a period-scale decrease in the degree and intensity of chemical weathering up section. The general absence of kaolinitic paleosols in Dunkard strata relative to the abundance of Pennsylvanian kaolinitic paleosols also indicates greatly diminished weathering while Dunkard strata were being deposited relative to these earlier times when coal-resource-bearing Pennsylvanian strata were being deposited.

DUNKARD GROUP DEPOSITIONAL ENVIRONMENTS

Deposition of strata within the Dunkard Group has been attributed to alluvial plain and lacustrine depositional environments (e.g., Beerbower, 1961, 1964, 1969; Berryhill and Swanson, 1962; Berryhill, 1963; Martin, 1998). In the present study, the alluvial plain environment is interpreted as a low gradient alluvial fan where autocyclic fan drainages discharged from the south-southeast (Martin, 1998) into a lacustrine basin along the synclinal axis of the present-day basin center. Laterally fluctuating facies between the autocyclic alluvial plain sedimentation and allocyclic lacustrine conditions is indicated by intertonguing of laterally extensive beds of lacustrine origin (coal beds, limestones, and fan-delta lacustrine siliciclastic rocks) with strata of alluvial plain origin. Some limestone units have been traced southward from the lacustrine basin center into coeval petrocalcic paleo-Vertisols that formed on the alluvial plain. The lateral extent of the limestone and the coeval petrocalcic-Vertisols is indicative of a time of low siliciclastic sediment input in response to a dry-subhumid to semiarid paleoclimate.

The diminishing lateral extent of coal beds and limestones up-section (see cross section by Fedorko, included with the CDROM of this guidebook) suggests that lacustrine conditions became more restricted spatially through time. Figure 3 presents a schematic cross section depicting alluvial fan and lacustrine basin depositional settings.

Base level fluctuations are recorded in Dunkard Group strata, especially in the lithostratigraphy in the basin center. Well developed regional-scale basin-center paleosols are indicative of well-drained soils and a subsurface water table when base level migrated beyond the basin. In contrast, nonmarine limestones, coal beds, and fan-deltas, are indicative of relatively high intra-basinal base levels and a variety of lacustrine conditions. The common stratigraphic succession of paleosol, limestone and/or coal, dark shale, conformably overlain by flat-bottom sandstone is indicative of rising water level and the onset of lacustrine conditions.

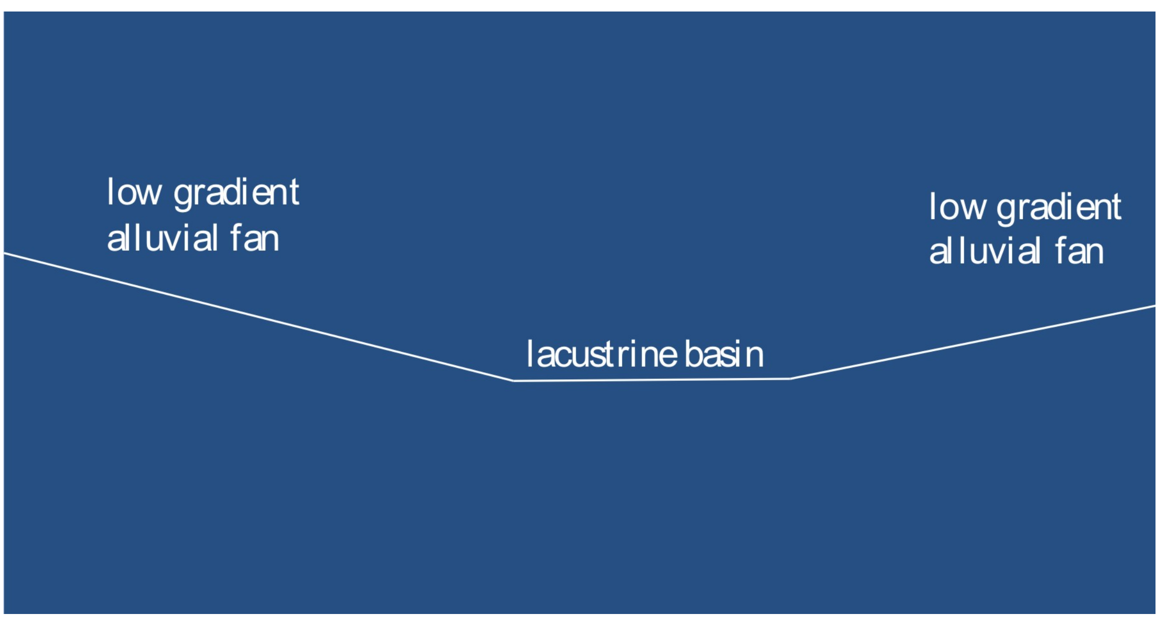


Figure 3. Schematic cross section illustrating a low gradient alluvial fan and a lacustrine basin.

Mineral Paleosols

An extensive variety of paleosols occurs in the Dunkard Group, ranging from Inceptisols to petrocalcic-paleo-Vertisols. Inceptisols are common in alluvial plain sequences where soil horizonation is not developed, but root traces indicate incipient soil formation. Inceptisols are common in aggrading alluvial plain sequences. Hydromorphic Histosols include coal beds and certain dark shales. Plant fossils in the dark shales are indicative of waterlogged conditions and a clastic swamp (see the description of Stop 4, Rosby's Rock). The frequency of occurrence and thickness of hydromorphic paleosols decrease up section. Soils underlying coal beds (underclays) analogous to the humid climate paleosols that underlie the thick, mineable, Pennsylvanian coal beds are poorly developed at best or not developed at all in the Dunkard. The paucity of well developed underclays is indicative of the relatively dry climates that prevailed during Dunkard deposition.

Vertisols with petrocalcic horizons and nodules are common, especially in the upper half of the Dunkard Group. The seat rock (underclay) beneath the Waynesburg A coal bed (Waynesburg Formation) is apparently the oldest petrocalcic-Vertisol in the Dunkard. The regional distribution of the petrocalcic-Vertisol under the Waynesburg A coal is indicative of landscape topography and a paleosol catena where a paleosol developed on topographic highs and lacustrine carbonate developed in topographic lows, as is the case below the Waynesburg A coal at the Roberts Ridge Road stop (Stop 2). Nonetheless, petrocalcic-Vertisols are very common in younger strata, especially in the Greene Formation (Figure 4).

Coal Beds

The Dunkard Group is known for its lack of coal resources (the upper barren measures of Rogers, 1858) (see cross section by Fedorko, on the CDROM of this guidebook). With the exception of the Waynesburg coal, which marks the base of the Dunkard, only the Washington coal complex has been mined locally, but it never represented a significant coal resource. Other Dunkard coal beds are generally thin and rather discontinuous although coal bed horizons can be traced regionally (see Fedorko and Skema, 2011). In addition, where coal does occur, generally it is relatively high in ash yield and sulfur content (see Eble et al., 2011). All the characteristics of Dunkard Group coal beds are suggestive of both topogenous (ground and surface water peat hydrology) and eutrophic (high dissolved solutes) conditions of peat formation (see Cecil et al., 1985, p. 202). In addition, coal underclay paleosols generally are thin and poorly developed relative to underclay paleosols that underlie Pennsylvanian coal beds that contain or did contain significant coal resources prior to mining. In short, conditions of peat formation during deposition of the Dunkard Group were marginal at best (see Cecil et al., 1985 for a more comprehensive treatment of factors that control peat formation). Coal beds are indicative of waterlogged peat swamps whereas the overlying dark gray shales are interpreted as lacustrine prodelta deposits.

Limestones

Limestones in the Dunkard Group (see Fedorko and Skema, 2011, for the stratigraphy of Dunkard limestones) appear to be of lacustrine origin. The predominant primary lithologies common to many of the Dunkard Group limestones are ostracode-peloidal wackestones and packstones (Isabel Montanez, 2011, personal communication). Limestones, most common in the Waynesburg and Washington formations, are composed of multiple benches that contain

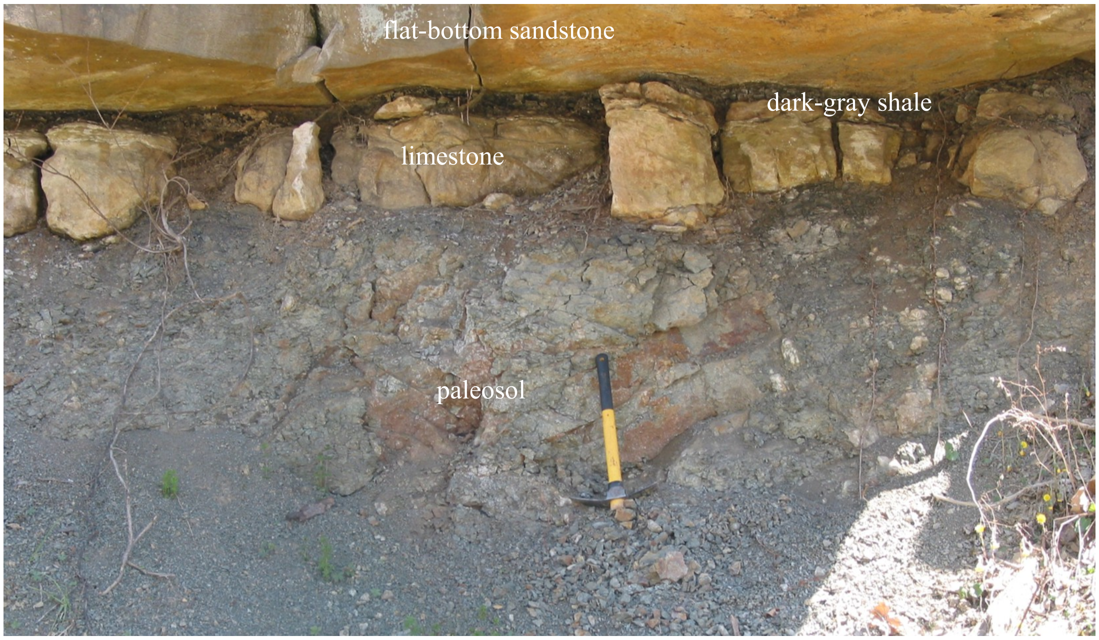


Figure 4. Petrocalcic Vertisol (unit with mattock for scale) in the Greene Formation overlain by the blocky Middle Rockport lacustrine limestone (buff), thin dark gray shale, and flat-bottom sandstone (top of photo) respectively. The dark gray shale occupies the stratigraphic position coal. Coal is not present at this locality. Mattock handle in the center of the photo is 40 cm (1.3 ft). Outcrop is on Greathouse Hill Road, Wetzel Co., WV.

subaerial macroscopic features such as subaerial crusts, micro-karsting, and brecciation induced by pedogenic processes similar to most Pennsylvanian nonmarine limestones including the Middle Pennsylvanian Upper Freeport limestone (Cecil, et al., 1985). The complex of limestone beds with subaerial exposure features suggests repeated rise and fall of water within carbonate-rich lakes. In contrast, limestones in the Greene Formation sometimes consist of a single bed without well developed subaerial features, and may contain plant fossils, such as tree ferns, typical of relatively abundant soil moisture (perhaps growing on the lake margins). Again, though, the Greene Formation is more or less confined to the lacustrine basin center and, therefore, potentially less well drained and wetter relative to the alluvial plain.

The carbonate-rich lakes were desiccated periodically either by draining, or by evaporation during relatively dry intervals. Evaporation should have led to increased salinity, but, except for some dolomitic beds, field evidence for increased salinity has not been reported. If drainage was the cause, then the nonmarine carbonate systems must have been somewhat analogous to the fresh water marls in the Florida Everglades, where a small drop in sea level in Florida Bay would result in drainage of the Everglades. Subsequently, the entire fresh-water lacustrine-palustrine Everglades system would disappear and subaerial exposure of the fresh water marls would lead to subaerial crusts and brecciation similar to those features in Pennsylvanian nonmarine limestones. Such small-scale sea-level fluctuations might also account for the multiple benches of limestone within individual named limestone units such as the Benwood in the Monongahela Group or the Washington in the Dunkard. A distal connection to the sea, and hence to sea level influences, perhaps through a breach in a sill represented by the Cincinnati arch, would also explain the apparent time-stratigraphic correlation of marine and nonmarine limestones (Cecil et al., 2003a). The Gulf of Carpentaria in Northern Australia represents an alternative to the Florida Everglades for carbonate deposition. Eustatic cycles appear to have been an allocyclic control on the Pleistocene/ Holocene stratigraphy of bottom sediments in the Gulf of Carpentaria basin (Edgar et al., 2003). Low stand exposure of the floor of the Gulf of Carpentaria basin contributed to the development of calcic-paleosols (Chivas et al., 2001). Subsequent ponding of drainage by sea level rise and lake formation could have led to lacustrine carbonate deposition.

Although sea level fluctuations could account for carbonate deposition and subsequent subaerial exposure, it does not appear that sea level fluctuations can account for high base level and deeper water conditions that led to fluvial-deltaic lacustrine deposition. Thus, unless definitive data become available that document a connection to sea level fluctuations, climate drying appears to be the cause of lake desiccation. Climate drying is also indicated by coeval alluvial plain paleosols containing petro-calcic features.

Sandstones and Shales

Sandstones and shales in the alluvial plain environment are the result of autocyclic fluvial processes (Beerbower, 1969). However, allocyclic changes in paleoclimate likely controlled stratigraphic variation in sediment supply as well as oxidation-reduction states in the alluvial plain environment.

Sediments were supplied to open-water lacustrine systems where fan deltas are indicative of fluvial deltaic progradation during lake level high stands. The dark gray shales that commonly overlie coal beds are interpreted herein as prodelta deposits. Flat-bottom sandstones, conformably overlying the dark gray shale facies, are interpreted as distributary mouth bars derived from fluvial progradation. Sandstones with an erosional base commonly incise the upper part of the flat-bottom sands. Incision, as indicated by these latter sandstones, is attributed to fluvial progradation analogous to the well-known fluvial incision of mouth bars by prograding distributaries in the Mississippi River delta (e.g., Tye and Coleman, 1989).

Recurring red bed units that extend from the alluvial plain into the basin center may have been the result of prograding alluvial fans during drier intervals when lake levels were low.

MODERN ANALOGUES

Two modern low-gradient alluvial fan complexes appear to approximate the dry and humid end-member climatic conditions that prevailed during deposition of the Dunkard Group. The Okavango Fan at the northern edge of the Kalahari Desert in Botswana (Milzow et al., 2009), southern Africa, appears to represent the dry climate end member condition during Dunkard deposition when dry climate paleosols extended from the upper alluvial plain into the basin center (Figures 5A and B). Standing water rarely if ever develops in the basin at the toe of the Okavango Fan complex. During the rainy season, water is delivered to the fan by rivers from headwaters outside the basin where it is mostly absorbed into soils or lost to evapotranspiration before reaching the basin.

In contrast to the Okavango fan, the alluvial fan complex along the eastern edge of the Pantanal in southern Brazil (Figures 6A and B) (Assine and Soares, 2004; Assine, 2005) is a likely candidate for the more humid climatic Dunkard conditions, when the alluvial plain was vegetated and lacustrine conditions developed in the basin center. In the modern Pantanal, the

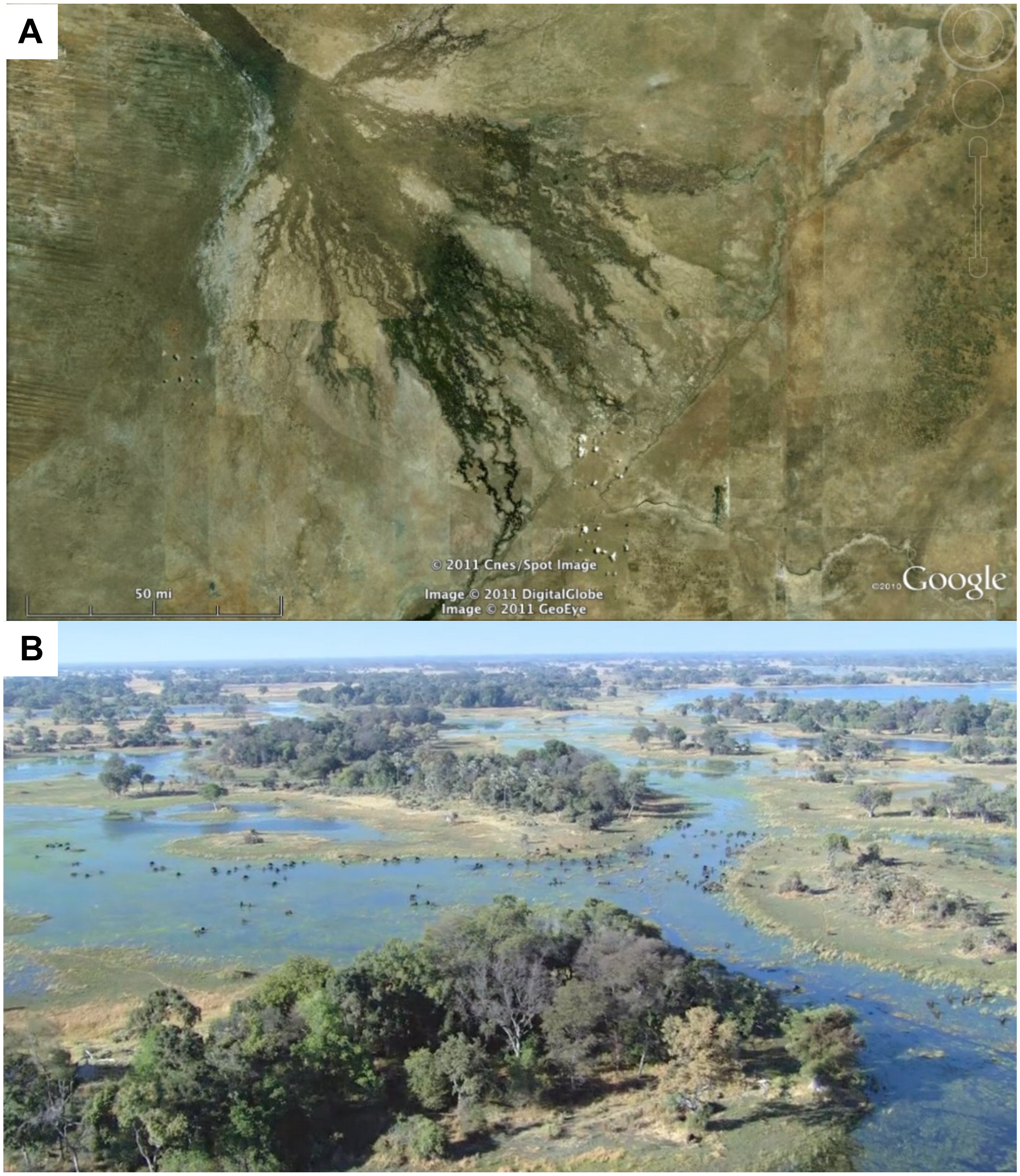
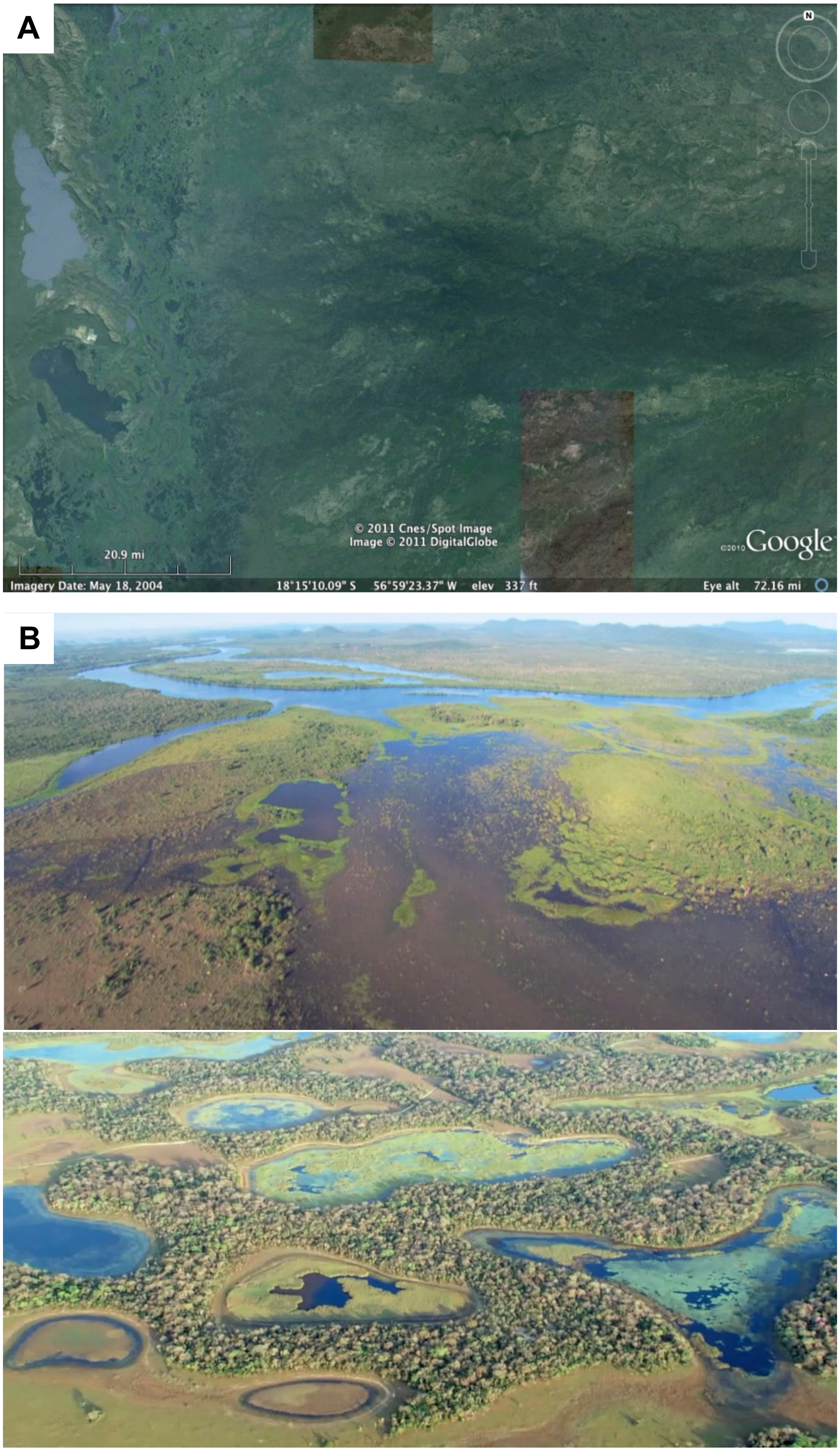


Figure 5. Photos of Okavango Fan in southern Africa. A—Okavango Fan as a dry climate analogue for dry periods on the Dunkard alluvial fan. Satellite view of the Okavango fan during the rainy season (source, Google Earth). Active fluvial drainages are indicated by anastomosing dark green colors. Scale – 2.54 cm = ~32 km (1 in = ~20 mi). B—Low altitude view of anastomosing streams and lakes on the vegetated Okavango fan surface during the rainy season (view is from *Planet Earth series).* Trees and large mammals (dark dots in streams) are indicative of scale. Roots of aquatic plants in streams are probable analogues of root traces in Dunkard fluvial mudstones and sandstones. Streams are dry during the dry season.

basin center is flooded during the rainy season, but is then desiccated to randomly distributed lakes during the dry season (Assine and Silva, 2009). The lack of flooding during the dry season may be mostly the result of drainage of the extremely low-gradient basin center rather than evapotranspiration. The lakes in the basin center appear to represent environments where either peat or limestone could form whenever the necessary water levels and chemistry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conditions are met. Either organic or carbonate sedimentation in scattered lakes in the Pantanal basin center may be analogous to the discontinuous coal beds or limestones in the Dunkard.

The extent of stage-scale climate change in the Okavango and Pantanal regions is not known. Neither is the effect of climate and climate change as a control on sedimentation and stratigraphy. An extensive coring program in these two regions could certainly help elucidate autocyclic and allocyclic controls on sedimentation and stratigraphy in low-gradient fan systems. The results of modern analogue studies would almost assuredly help unravel the genetic controls on ancient alluvial systems such as the Dunkard Group.

The semiarid region of the Gulf of Carpentaria basin, Northern Australia, may represent a good analogue for Pennsylvanian deposition during the Missourian dry interval when mixed marine and nonmarine strata were deposited. Given the elevation of the Gulf basin, it can only be a partial analogue for Dunkard deposition because of marine flooding during high stands. Low stand paleosols overlain by ancient lake sediments beneath modern marine sediments in the Gulf are prototypes for paleosol types and lacustrine limestones (Edgar, et al., 2003; Chivas et al., 2001). Drainage gradients in the predominant fluvial source areas to the south of the Gulf are less than 10.6 m per km (< 2 ft per mi).

SUMMARY AND CONCLUSIONS

Determination of the relative importance of autocyclic and allocyclic processes provides a comprehensive analytical method by which the origin of alluvial-lacustrine depositional systems can be determined. Although Beerbower (1964) attempted to use the Mississippi River delta as a modern analogue for Dunkard stratigraphy, it now appears that modern fan-basin systems such as the Okavango and Pantanal are much better analogues, particularly in terms of stream gradients on the fan and in basin centers, as well as climate end-member conditions.

It also appears that autocyclic processes dominated alluvial plain sedimentation whereas allocyclic climate changes, ranging from humid to dry subhumid and perhaps even semiarid dominated the lacustrine systems . Alternating red and green strata are indicative of sediments that were either oxidizing and relatively dry (red) or waterlogged (green) by both autocyclic alluvial plain processes or by allocyclic changes in paleoclimate.

In contrast to the alluvial plain, allocyclic processes predominantly controlled basin center deposition and stratigraphy. However, stage-scale climate cycles (cyclothems), so apparent during the Pennsylvanian (Cecil, 1990), became increasingly less extreme and less distinct during Dunkard deposition. As in the upper alluvial plain, stage-scale climates ranged from humid to dry-subhumid or even semiarid (Figure 7). Humid periods led to a variety of waterlogged and base level conditions that determined peat formation, limestone deposition, or lacustrine deltaic sedimentation. Dry stages resulted in basin exposure and basin-scale calcic

Figure 6 (opposite page). Photos of the Pantanal fan in southern Brazil. A—Satellite image of the Pantanal fan and basin (area with lakes on the left-side of photo) as a humid climate analogue for humid periods on the Dunkard alluvial fan and basin (source, Google Earth). Low gradient active fluvial drainages on the fan are indicated by westward flowing anastomosing streams (darkest green colors) from the right center toward the center of the photo. Scale – 2.54 cm = ~32 km (1 in = ~20 mi). Lakes ~32 km (~20 mi) in length are visible on the left side of the photo. B—Two low altitude views of the Pantanal basin surface during the dry season (views are from the *Planet Earth series).* The region is flooded and under water during the rainy season. Trees and dirt road in the upper left corner of the bottom photo are indicative of scale. Vegetated lakes and ponds are potential analogues for the discontinuous Dunkard coal beds.

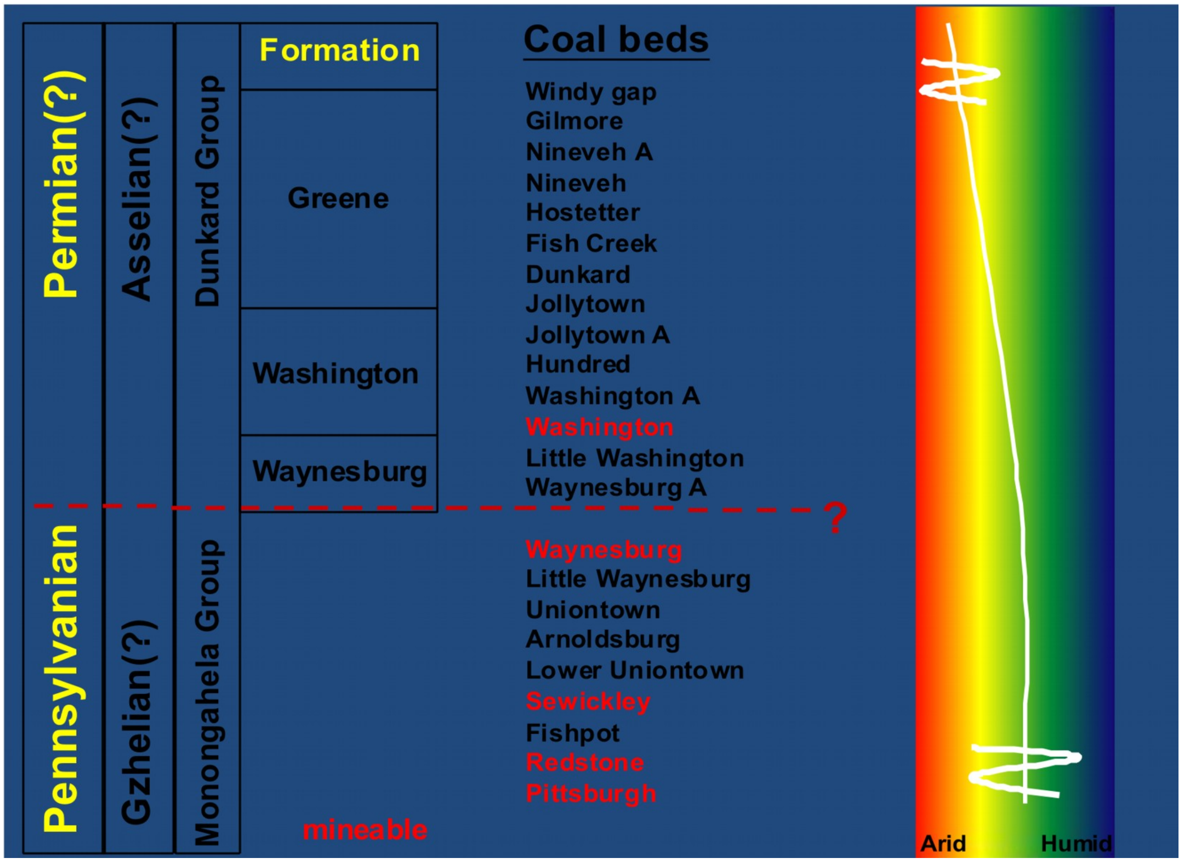

Figure 8. Stratigraphy of Monongahela Group and Dunkard Group coal beds. The diagram on the right side of the figure illustrates the period-scale climate transition and stage-scale climate cycles.

paleosols. These stage-scale paleoclimates became increasingly dampened, as they were part of a period-scale climate transition (Figure 7).

It is more difficult to explain the period-scale climate drying transition that began during deposition of the Late Pennsylvanian Monongahela Group and progressed during deposition of approximately 366 m (1,200 ft) of preserved Dunkard strata (Figure 7). Period-scale climate drying observed in Dunkard strata may have been caused by the assembly of Pangea (Parrish, 1993). If the Dunkard basin was positioned in the Pangean interior, it was far removed from a moisture source. A temporal increase in rainout, as prevailing equatorial winds moved from coastal regions toward the continent interior, would have caused period-scale climate drying (e.g. Tabor and Poulsen, 2008). Another factor in the slow drying trend may have been the rise of the central Pangean mountains and the slow development of a rain shadow over the Dunkard basin and beyond. Regardless of the cause(s), a time-stratigraphic drying trend, as shown in Figure 7, is indicated by the following: a) a stratigraphic increase in syngenetic calcite, b) a decrease in coal bed occurrence and thickness, c) a decrease in coal quality, and d) an increase in the occurrence of petrocalcic-paleosols.

The period-scale trend in climate drying represented in the approximately 366 m (1,200 ft) of Dunkard strata probably lasted for at least 10 million years and at least some, if not most, of the Dunkard is Permian (Asselian to Kungurian; see Lucas, 2011). If so, then Dunkard deposition was coeval with the transition between the humid Late Carboniferous and the arid late Permian (Kungurian in Russia) (summarized by Wardlaw et al., 2004).

ACKNOWLEDGEMENTS

This paper is dedicated to the memory of Prof. James R. (Dick) Beerbower whose pioneering work on the origin of the Dunkard led to his formulation and declaration of autocyclic and allocyclic models of sedimentation and stratigraphy.

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